Incorporating Optics into a Coupled Physical-Biological Forecasting System in the Monterey Bay

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LONG-TERM GOALS

Modeling and predicting ocean optical properties for coastal waters requires linking optical properties with the physical, chemical, and biological processes in the upper ocean. Our long-term goal is to incorporate optical processes into coupled physical-biological models for coastal waters, develop and improve integrated ocean forecasting systems, including prediction of ocean optical properties.

OBJECTIVES

1) To improve performance of the coupled physical-biological model, which is based on the Regional Ocean Model System (ROMS), for the Monterey Bay;

2) To incorporate optical variables into a one-dimensional (1D) physical-biological as well as the improved coupled 3D physical-biological model for the Monterey Bay;

3) To use these variable to drive a radiative transfer model (HydroLight/EcoLight) that will simulate and predict the subsurface light field as well as the ocean's color;

4) To conduct ROMS-biological-optical model simulations for the Monterey Bay with focus on two intensive field experiments, ANOS II (August 2003) and Monterey Bay 2006 (August 2006), and use the bio-optical measurements to constrain and improve the models.

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14. ABSTRACT

Modeling and predicting ocean optical properties for coastal waters requires linking optical properties with the physical, chemical, and biological processes in the upper ocean. Our long-term goal is to incorporate optical processes into coupled physical-biological models for coastal waters, develop and improve integrated ocean forecasting systems, including prediction of ocean optical properties.

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APPROACH

Our approach is to incorporate spectrally-resolved inherent and apparent optical properties into a one-dimensional (1D) multi-nutrient, phytoplankton, zooplankton and detritus ecosystem model. By comparing the bio-optical model output with *in situ* and satellite ocean color measurements, we highlight the fact that optical properties play an important role in identifying and reducing uncertainties in ecosystem models, which provide constraints for determining variables and related parameters. Our long term goal is to incorporate the improved 1D bio-optical modeling into the Regional Ocean Model System (ROMS) for the Monterey Bay, and make prediction of coastal ocean's optical properties on time scales of 1 to 5 days, i.e., the time scales of accurate atmospheric forecasts.

The modeling system constructed in this study consists of four individual models, physical-ecosystem model, photo-acclimation model, optical model, and radiative transfer model. The physical-ecosystem model used in this study is based on the Carbon, Silicon, Nitrogen Ecosystem (CoSINE) model (Chai et al., 2002), which was originally developed to simulate biogeochemistry in the equatorial Pacific upwelling region. To reproduce observed variation in phytoplankton chlorophyll to carbon ratio with growth conditions (light, nutrients and temperature), Geider et al. (1987, 1998) developed a photo-acclimation model with single nutrient of nitrogen. Moore et al. (2002) modified the photo-acclimation model so that the model could be embedded in multi-nutrient ecosystem model, which was used in this study. We developed an optical model that explicitly represents spectrally-resolved IOPs (absorption, scattering and attenuation), apparent optical properties (AOPs, such as diffuse attenuation), and radiometric quantities such as PAR. The optical model requires the inputs from the physical-ecosystem model, such as phytoplankton associated chlorophyll and non-algal particles (NAP). The radiative transfer model (Ecolight; Sequoia Scientific, Inc.) provides downwelling irradiance at sea surface and underwater average cosines of downwelling light (from 400 to 700 nm), and the hourly values are used as external forcing for the optical model. The physical-ecosystem model, photo-acclimation model, optical model and radiative transfer model are connected as one bio-optical modeling system. We applied this system to the equatorial Pacific upwelling region (5°S-5°N, 90°-180°W, the "Wyrtki Box"), where the physical-ecosystem model originally developed (Chai et al., 2002) and some optical properties have been measured for this region (Gardner et al., 2003; Behrenfeld et al., 2006).

WORK COMPLETED

This report summarizes modeling activities between 1 October 2006 and 30 September 2007.

We have completed the equatorial modeling effort. This includes:

1. Developed a bio-optical module that translate the biogeochemistry into inherent optical properties (IOPs).
2. Incorporated a radiative-transfer model that predicts the subsurface light field given the IOPs.
3. Performed a sensitivity study to the parameters of the bio-optical module based on their uncertainties (see Table 1 below).
4. Compared our results with IOPs measured in situ.
5. Presented our results in the Ocean Optics conference and had our results peer-reviewed and published in the journal Biogeosciences (Fujii et al., 2007).
6. Assembled a dataset of all the IOPs in Monterey Bay, which will be the site of our next modeling effort.

RESULTS

Given that in our past reports we focused on the matchup between modeled and observed properties here we focus on a sensitivity analysis to the bio-optical model. Such analysis, to our knowledge, has never been performed and provided many lessons for us regarding what is and what is not essential to include in the model.

The values of parameter chosen for this study are based on observations but the observed values have substantial variability that arises from environmental and methodological variability. To elucidate how model results are affected by variations in the optical model parameters, we conducted a sensitivity study of the model to those parameters by changing their values individually by 30% of their standard values. Such variability encompasses the bulk of observed values (Table 1).

Table 1. Sensitivity of model results to optical parameters: Carbon-specific absorption coefficient by NAP at 440nm ($a^{+}_{NAP}(440)$), absorption coefficient by CDOM at 440nm ($a_{CDOM}(440)$), background backscattering coefficient (b_{bbg}), ratio of phytoplankton carbon to POC (R^{φ}_{POC}), backscattering ratio for picoplankton ($\tilde{b}_{b\_P1}$), diatoms ($\tilde{b}_{b\_P2}$), NAP ($\tilde{b}_{b\_NAP}$), and background particles ($\tilde{b}_{b\_bbg}$). Values in parentheses denote model results from a control run with bio-optical model. Euphotic layer depth is defined as a depth of 0.1% of sea surface. Sources noted here are: (1) Babin et al., 2003a and 2003b; (2) Simeon et al., 2003; (3) Stramski and Kiefer, 1991, Cho and Azam, 1990, and Behrenfeld and Boss, 2006; (4) Eppley et al., 1992, DuRand et al., 2001, Gundersen et al., 2001, and Oubelkheir et al., 2005; (5) Twardowski et al., 2001; (6) Twardowski et al., 2001, and Boss et al., 2004.

Parameter	Observed values	Value for sensitivity study	Surface NO_3 ($mmolm^{-3}$) (6.6)	Surface $Si(OH)_4$ ($mmolm^{-3}$) (2.2)	Maximum chlorophyll ($mgChlm^{-3}$) (0.34)	Depth of maximum chlorophyll (m) (50)	Mean $a_{NAP}/a_p(440)$ above 100m (0.15)	Mean C_p (660) above 100m (m^{-1}) (0.069)	Euphotic layer depth (m) (115)
$a^{+}_{NAP}(440)$	0.1[(1)]	0.07-0.13 (0.1)	6.4-6.7	2.0-2.3	0.33-0.35	50	0.10-0.20	0.068-0.070	115
$a_{CDOM}(440)$	0.012-0.025[(2)]	0.011-0.021 (0.016)	5.7-7.1	1.7-2.9	0.31-0.38	60-85	0.14-0.17	0.066-0.072	110-120
b_{bbg}	0.00017[(3)]	0.00012-0.00022 (0.00017)	6.6	2.1-2.2	0.34	60	0.15	0.066-0.071	115
R^{φ}_{POC}	0.25-0.4[(4)]	0.21-0.39 (0.3)	6.5-6.7	2.1-2.2	0.34	50-55	0.15	0.059-0.086	115
$\tilde{b}_{b\_P1}$	0.01-0.013[(5)]	0.007-0.013 (0.01)	6.6	2.2	0.34	50	0.15	0.065-0.076	115
$\tilde{b}_{b\_P2}$	0.006-0.007[(6)]	0.004-0.008 (0.006)	6.6	2.2	0.34	50	0.15	0.067-0.073	115
$\tilde{b}_{b\_NAP}$	0.015-0.02[(5)]	0.011-0.020 (0.015)	6.6	2.2	0.34	50	0.15	0.061-0.083	115
$\tilde{b}_{b\_bbg}$	0.02[(5)]	0.014-0.026 (0.02)	6.6	2.2	0.34	50	0.15	0.067-0.073	115

We found the model results of biogeochemical properties, i.e., surface NO_3, $Si(OH)_4$, and maximum chlorophyll and its associated depth, to be most sensitive to changes in the absorption coefficient by CDOM at 440nm ($a_{CDOM}(440)$). The surface NO_3 increases and $Si(OH)_4$ decreases with the increase of $a_{CDOM}(440)$, due to an increase in contribution by diatoms when $a_{CDOM}(440)$ is higher. The maximum chlorophyll decreases and appears at a deeper layer of 85m with an $a_{CDOM}(440)$ increase. These model results reveal that the CDOM concentration strongly affects phytoplankton community structure and its dynamics. While CDOM's inherent effects on backscattering and hence beam attenuation coefficient at 660nm ($C_p(660)$) are negligible, an increase of $a_{CDOM}(440)$ yields a $C_p(660)$ decrease due to a decrease in small algal POC. The modeled euphotic layer depth, defined as a depth of 0.1% light level of sea surface, decreases from 120m to 110m by varying $a_{CDOM}(440)$ from 0.011 to 0.021 (m^{-1}), primarily as a result of enhanced absorption by CDOM. The change of the euphotic layer depth is relatively small because PAR is more controlled by absorption by water than absorption by underwater particle and CDOM concentration. However, the euphotic layer depth is more sensitive to $a_{CDOM}(440)$ than to the other optical parameters due to significant absorption by CDOM at short wavelengths around 400nm, at which absorption by water is negligible.

The observed sensitivity to CDOM concentration is the result of CDOM absorbing light that would otherwise be absorbed by phytoplankton. This effect is more pronounced on picoplankton as they have a relatively higher portion of their energy absorbed in the blue wavelength where CDOM absorbs (they are less packaged and thus have a higher blue to red absorption ratio). Changes in the relative abundance of small and large phytoplankton results in a change in the biogeochemical properties of the upper ocean since their metabolic requirements and interaction with other trophic levels are different. Variation in other optical parameters also contributed to changes in the model results, but their impact is smaller than that of $a_{CDOM}(440)$. The carbon-specific absorption coefficient by NAP at 440nm ($a^{+}_{NAP}(440)$) has weaker but similar effects on surface nutrient and maximum chlorophyll concentration as $a_{CDOM}(440)$. The modeled $a_{NAP}/a_p(440)$ is the most sensitive to $a^{+}_{NAP}(440)$, changing by a factor of 2 from 0.10 to 0.20. The modeled $C_p(660)$ is affected most significantly by the ratio of phytoplankton to particulate organic carbon (R^{φ}_{POC}). The modeled euphotic layer depth does not change from the standard value of 115m by changing any optical parameters except for $a^{+}_{NAP}(440)$, which indicates the important role of absorption in the lower layer below chlorophyll maximum in determining the euphotic layer depth. Varying any of the backscattering ratios, regardless of particle type, does not affect the modeled biogeochemical properties but does influence $C_p(660)$. However, the sensitivity of $C_p(660)$ to the backscattering ratios depends on particle type, being stronger for NAP and picoplankton and weaker for diatoms and background particles, reflecting the higher backscattering coefficient by picoplankton than by diatoms.

The overall sensitivity study shows that narrowing the observed ranges of optical parameters above is required to reduce uncertainties in reproducing biogeochemical properties. In addition, the above analysis suggests that although the dynamics of neither CDOM nor bacteria are currently incorporated explicitly in the model, embedding CDOM as a state variable in the ecosystem model should be given priority over bacteria to improve simulating bio-optical interactions. We will use these results in our future development of the model.

We developed an ecosystem model that explicitly represents biogeochemically and optically two phytoplankton and two zooplankton functional groups, as well as multiple nutrients and non-algal particles (NAP). We applied the model to the equatorial Pacific upwelling region and found that utilizing an optical model to convert from ecosystem model state variables to optical parameters and a realistic subsurface light provides: (1) more data to compare model output with providing a more rigorous test on model formulation and choice of parameter values, especially for those that are difficult to measure in high resolution in time and space, (2) the required input to obtain a realistic subsurface light field by linking the optics to a radiative-transfer model (Ecolight), and (3) improved simulation realism with respect to key biogeochemical processes, such as photosynthesis, which are crucial for assessing oceanic carbon cycling and food web dynamics. The additional optical measurements, being routinely available from research vessels, autonomous platforms, and space-borne observations, can now be used directly for comparison and testing of the output of our new coupled bio-optical model. This is an improvement over the limited number of variables that can be used to test our previous ecosystem models with no explicit optical properties. Model sensitivity studies on optical parameters suggest that CDOM may have an important role in phytoplankton dynamics, nutrient cycling, and light field in the euphotic layer.

In preparation of transitioning to a 3-D modeling effort of Monterey Bay we have assembled a large data set of biochemical and bio-optical data (for spatial coverage, see Fig. 2). This is one of the densest bio-optical data ever collected that will be used to refine our bio-optical model and test our results against. We plan to collaborate with the scientists involved in collecting these data for modeling and data analysis for the Monterey Bay region.

IMPACT/APPLICATIONS

Incorporating ocean optical processes into coupled physical-biological models will enable us to simulate and forecast optical properties in coastal waters. With demonstration of some initial successes of developing physical-biological-optical modeling and data assimilation capability for Monterey Bay, we should be able to start the development of an end-to-end ocean forecasting system. Such modeling system would be a powerful tool to design the adaptive sampling strategy and would be an essential component of future field experiments both in and outside Monterey Bay.

TRANSITIONS

We have worked with Drs. John Kindle, Igor Shulman, and Bred Penta at the Naval Research Laboratory (NRL). The ecosystem model code has been transferred to the Dynamics of Coupled Processes group led by John Kindle at the NRL. The ecosystem model has been implemented into both Navy Coastal Ocean Model (NCOM) and Princeton Ocean Model (POM) for the west cost of U.S. and Monterey Bay region. Fei Chai traveled to the NRL in late August of 2005 to work on some issues regarding to the ecosystem component in the NCOM. Fei Chai will visit NRL in November 2007 for the ongoing and further collaboration between the University of Maine and NRL. We have regular communications between the NRL and the University of Maine on this collaboration. The improved ecosystem model and the optical module will be transited to the NRL Dynamics of Coupled Processes group.

RELATED PROJECTS

This project has strong collaboration with other ONR supported projects. Besides working closely with the modeling group at the NRL, we are collaborating with Dr. C. Mobley of Sequoia Scientific Inc. for better linking the optical module within the ROMS. We are also collaborating with scientists at the Monterey Bay Aquarium Research Institute (MBARI) for using the observational data for the region. Yi Chao is one of the investigators involved in the Monterey Bay 2003 and 2006 Experiments.

REFERENCES

Babin, M., Morel, A., Fournier-Sicre, V., Fell, F., and Stramski, D.: Light scattering properties of marine particles in coastal and open ocean waters as related to the particle mass concentration, Limnol. Oceanogr., 48(2), 843-859, 2003a.

Babin, M., Stramski, D., Ferrari, G. M., Claustre, H., Bricaud, A., Obolensky, G., and Hoepffner, N.: Variations in the light absorption coefficients of phytoplankton, nonalgal particles, and dissolved organic matter in coastal waters around Europe, J. Geophys. Res. 108(C7), 3211, doi:10.1029/2001JC000882, 2003b.

Behrenfeld, M. J., and Boss, E.: Beam attenuation and chlorophyll concentration as alternative optical indices of phytoplankton biomass, J. Mar. Res., 64, 431-451, 2006.

Behrenfeld, M. J., Boss, E., Siegel, D. A., and Shea, D. M.: Carbon-based ocean productivity and phytoplankton physiology from space, Glob. Biogeochem. Cycles, 19, GB1006, doi:10.1029/2004GB002299, 2005.

Boss, E., and Pegau, W. S.: The relationship of light scattering at an angle in the backward direction ot the backscattering coefficient, Appl. Optics, 40, 5503-5507, 2001.

Boss, E., Pegau, W. S., Lee, M., Twardowski, M. S., Shybanov, E., Korotaev, G.., and Baratange, F.: The particulate backscattering ratio at LEO 15 and its use to study particles composition and distribution. J. Geophys. Res., 109, C1, C0101410.1029/2002JC001514, 2004.

Chai, F., Dugdale, R. C., Peng, T. –H., Wilkerson, F. P., Barber, R. T.:, One-dimensional ecosystem model of the equatorial Pacific upwelling system. Part I: model development and silicon and nitrogen cycle, Deep-Sea Res. Part II, 49, 2713-2745., 2002.

Chai, F., Barber, R. T., and Lindley, S. T.: Origin and maintenance of high nutrient condition in the equatorial Pacific, Deep-Sea Res. Part II, 42(4-6), 1031-1064, 1996.

Cho, B. C., and Azam, F.: Biogeochemical significance of bacterial biomass in the ocean's euphotic zone, Mar. Ecol. Prog. Ser., 63, 253-259, 1990.

DuRand, M. D., Olson, R. J., and Chisholm, S. W.: Phytoplankton population dynamics at the Bermuda Atlantic Time-series station in the Sargasso Sea, Deep-Sea Res. Part II, 48, 1983-2003, 2001.

Eppley, R. W., Chavez, F. P., and Barber, R. T.: Standing stocks of particulate carbon and nitrogen in the Equatorial Pacific at 150ºW, J. Geophys. Res., 97, 655-661, 1992.

Fujii, M., E. Boss, and F. Chai (2007): The value of adding optics to ecosystem models: a case study. Biogeosciences 4, 1585-1631.

Gardner, W. D., Jo Richardson, M., Carlson, C. A., Hansell, D., and Mishonov, A. V.: Determining true particulate organic carbon: bottles, pumps and methodologies, Deep-Sea Res. Part II, 50, 655-674, 2003.

Geidar, R. J.: Light and temperature dependence of the carbon to chlorophyll a ratio in microalgae and cynobacteria: implications for physiology and growth of phytoplankton. New Phytol., 106, 1-34, 1987.

Geidar, R. J., MacIntyre, H. L., and Kana, T. M., A dynamic regulatory model of phytoplanktonic acclimation to light, nutrients, and temperature, Limnol. Oceanogr., 43, 679-694, 1998.
Gunderson, K., Orcutt, K. M., Purdie, D. A., Michaels, A. F., and Knap, A. H.: Particulate organic carbon mass distribution at the Bermuda Atlantic time-series Study (BATS) site, Deep-Sea Res. Part II, 48, 1697-1718, 2001.
Mobley, C. D., and Sundman, L. K.: Hydrolight 4.1 User's Guide (Sequoia Scientific, Inc., Redmond, Wash.), 2000a.
Mobley, C. D., and Sundman, L. K.: Hydrolight 4.1 Technical Documentation (Sequoia Scientific, Inc., Redmond, Wash.), 2000b.
Moore, J. K., Doney, S. C., Kleypas, J. A., Glover, D. M., and Fung, I. Y.: An intermediate complexity marine ecosystem model for the global domain. Deep-Sea Res. Part II, 49, 403-462, 2002.
Oubelkheir, K., Claustre, H., Sciandra, A., and Babin, M.: Bio-optical and biogeochemical properties of different trophic regimes in oceanic waters, Limnol. Oceanogr., 50, 1795-1809, 2005.
Pegau, W. S.: The distribution of colored dissolved organic matter (CDOM) in the Equatorial Pacific, Ocean Optics XIII, S. G. Ackleson, R. Frouin, Eds., 2963, 508-513, 1997.
Simeon, J., Roesler, C., Pegau, W. S., and Dupouy, C.: Sources of spatial variability in light absorbing components along an equatorial transect from 165ºE to 150ºW, J. Geophys. Res., 108(C10), 3333, doi:10.1029/2002JC001613, 2003.
Stramski, D., and D. A. Kiefer, D. A.: Light scattering by microzooorganisms in the open ocean, Prog. Oceanogr., 28, 343-383, 1991.
Twardowski, M. S., Boss, E., Macdonald, J. B., Pegau, W. S., Barnard, A. H., and Zaneveld, J. R.: A model for estimating bulk refractive index from the optical backscattering ratio and the implications for understanding particle composition in case I and case II waters, J. Geophys. Res., 106, 14129-14142, 2001.
Wyrtki, K.: An estimate of equatorial upwelling i 1 n the Pacific, J. Phys. Oceanogr., 11, 1205-1214, 1981.

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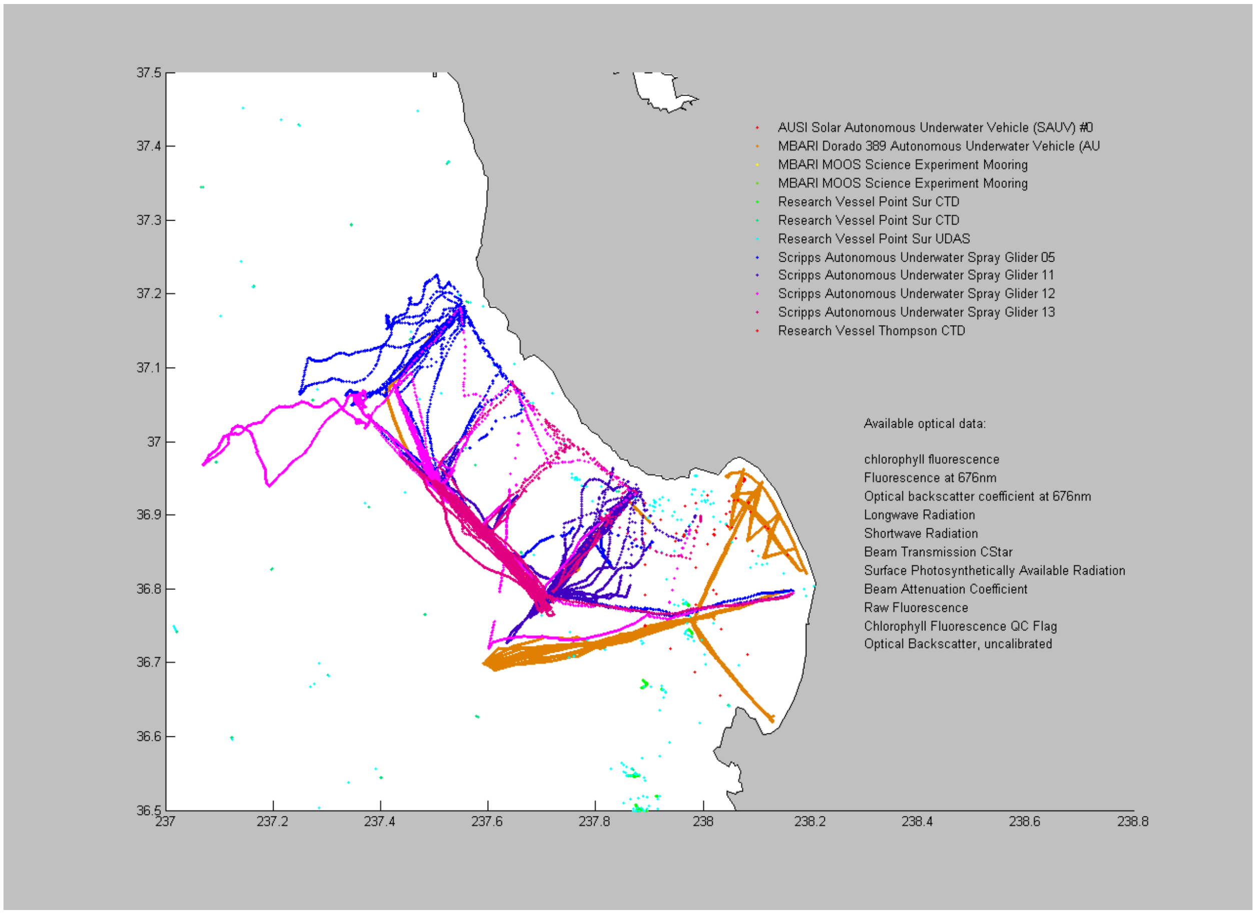

Figure 1: Cruise tracks and platforms that collected biological and optical information for the Monterey Bay. Optical data include: chlorophyll fluorescence, fluorescence at 676nm, optical backscatter at 676nm, beam transmission, beam attenuation coefficient, absorption coefficients, PAR, and many more.